Progress on ITER Diagnostics

Bringing state of the art diagnostics to nuclear machine

M. Kocan

On behalf of the ITER Diagnostics Program Team

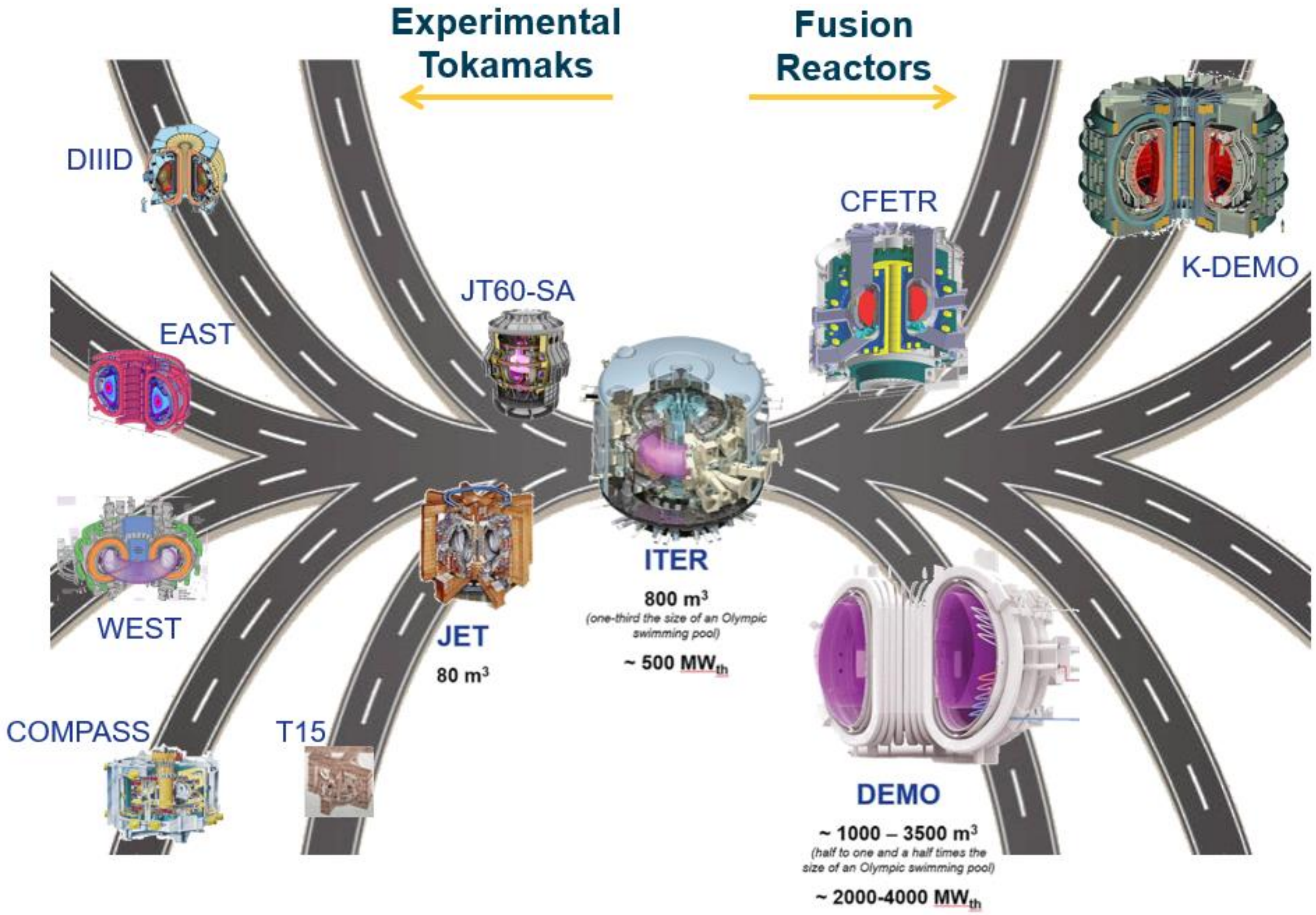
china eu india japan korea russia usa

Speaker’s resume

- PhD in Plasma Physics and Optoelectronics, working on Tore Supra tokamak – 2006-2009
- Postdoctoral researcher ASDEX Upgrade 2009-2012
  - Measurement of scrape-off layer turbulence using electric probes
  - Operation of infrared diagnostics
- Postdoctoral researcher at ITER Organization 2012-2014
  - Modelling of Edge Localized Modes
  - Optimization of the ITER first wall shaping
- 2014-2024: ITER Diagnostics, first as external contractor, then as Plasma Boundary Diagnostician and later as Coordinating Diagnostics Scientist for optical visible and infrared diagnostics, bolometers and fast ion loss detectors
- From 2024: Project Leader for 35 ITER diagnostics

Bringing state of the art diagnostics to nuclear machine

- Engineering of ITER diagnostic ports
- Diagnostics integration challenges
- Examples of manufactured and installed ITER diagnostics



Same diagnostics as in the current tokamaks but integrated into a nuclear reactor environment!

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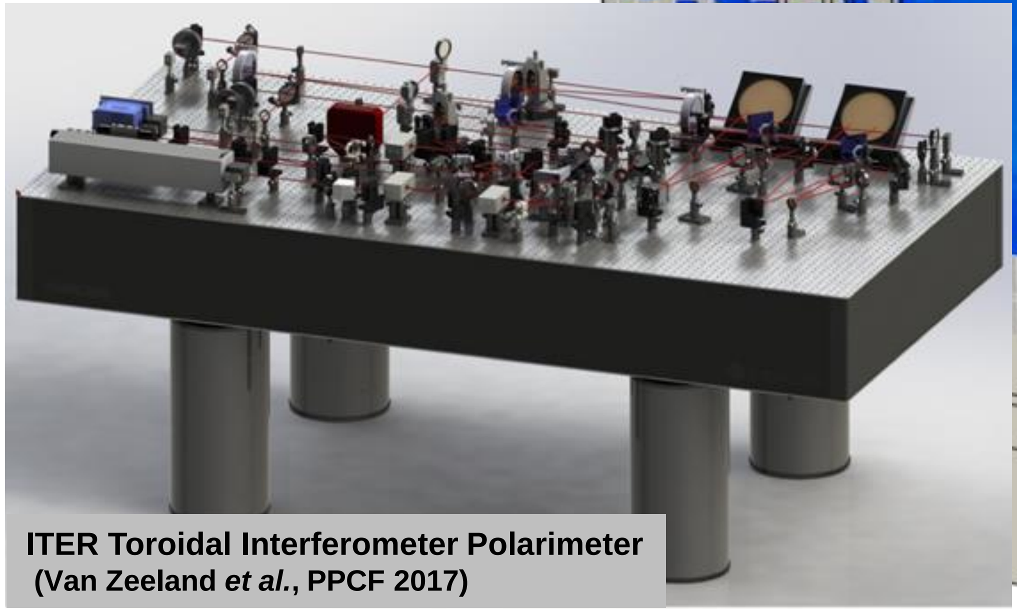
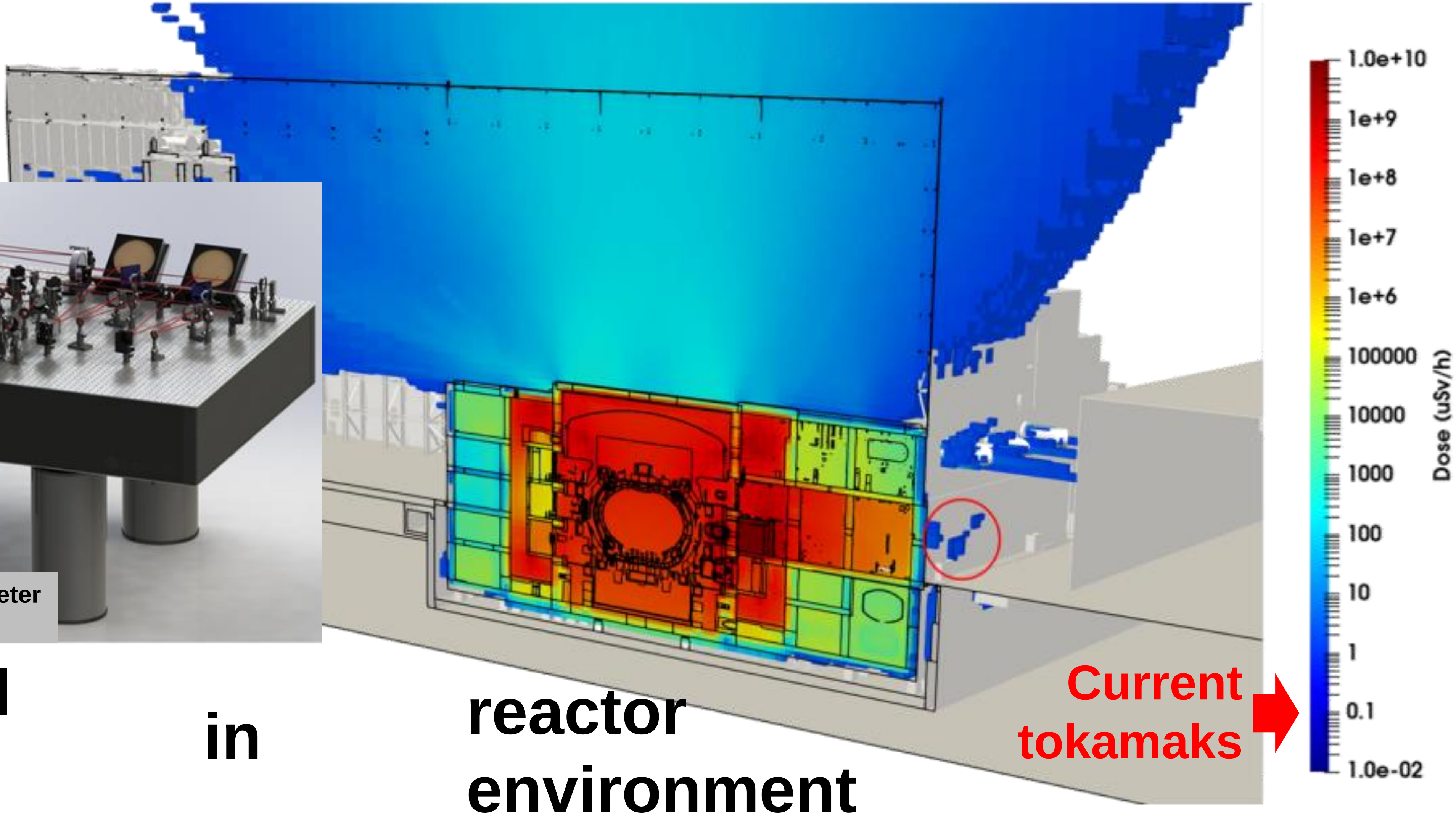


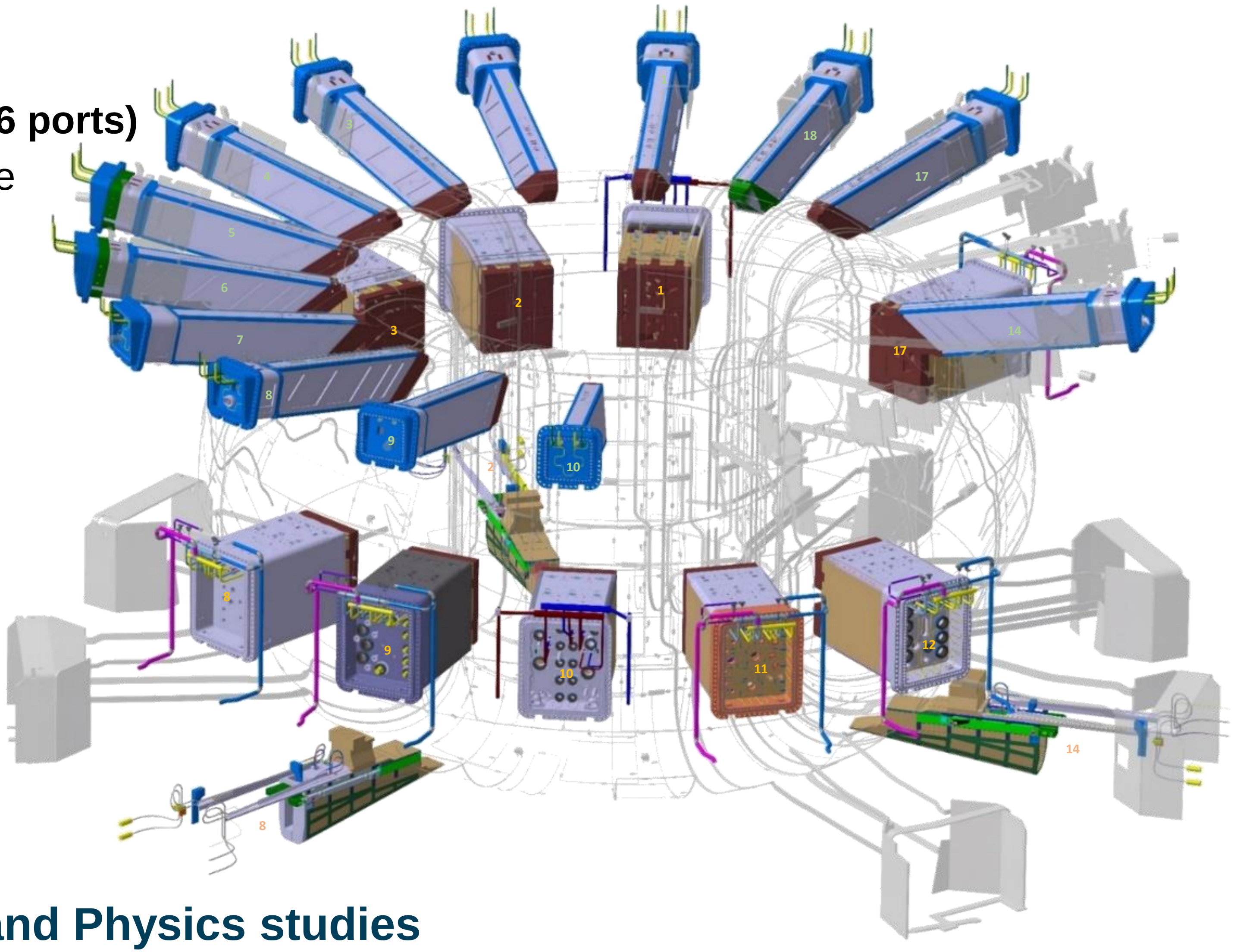
ITER Toroidal Interferometer Polarimeter
(Van Zeeland *et al.*, PPCF 2017)

experimental instrument **in** **reactor environment**



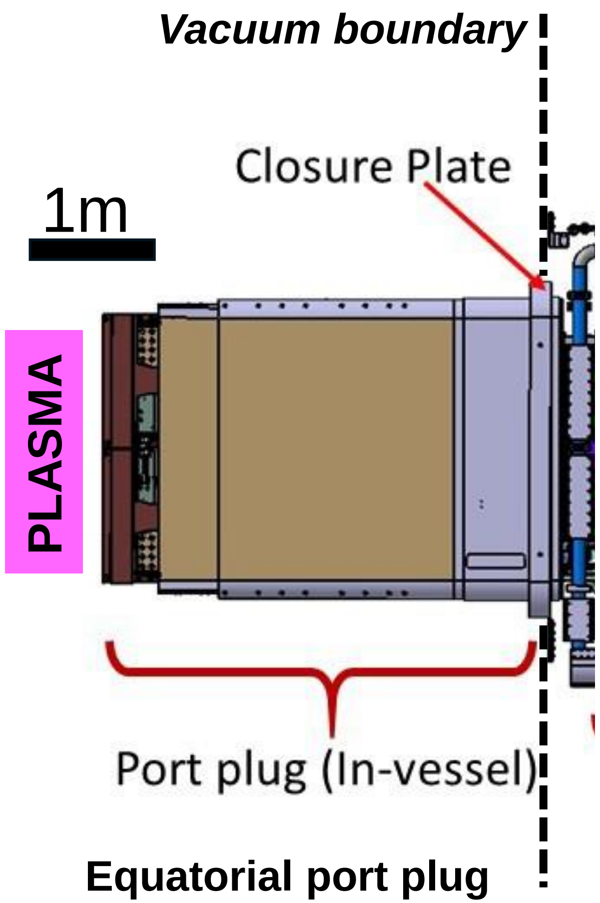
50 diagnostics measuring 100+ parameters

- **About 50 diagnostics**
  - **In the equatorial, lower and upper ports (26 ports)**
  - On the vacuum vessel, both inside the outside
  - In the divertor
  - On the first wall blankets
- **100+ plasma parameters**
  - Plasma current
  - Plasma shape and position
  - Temperature (core/edge)
  - Density (core/edge)
  - Plasma rotation and flow
  - Heat flux
  - Impurities
  - Wall conditions (wall erosion)
  - and many others…



- **Investment Protection, Plasma control and Physics studies**

Diagnostic port

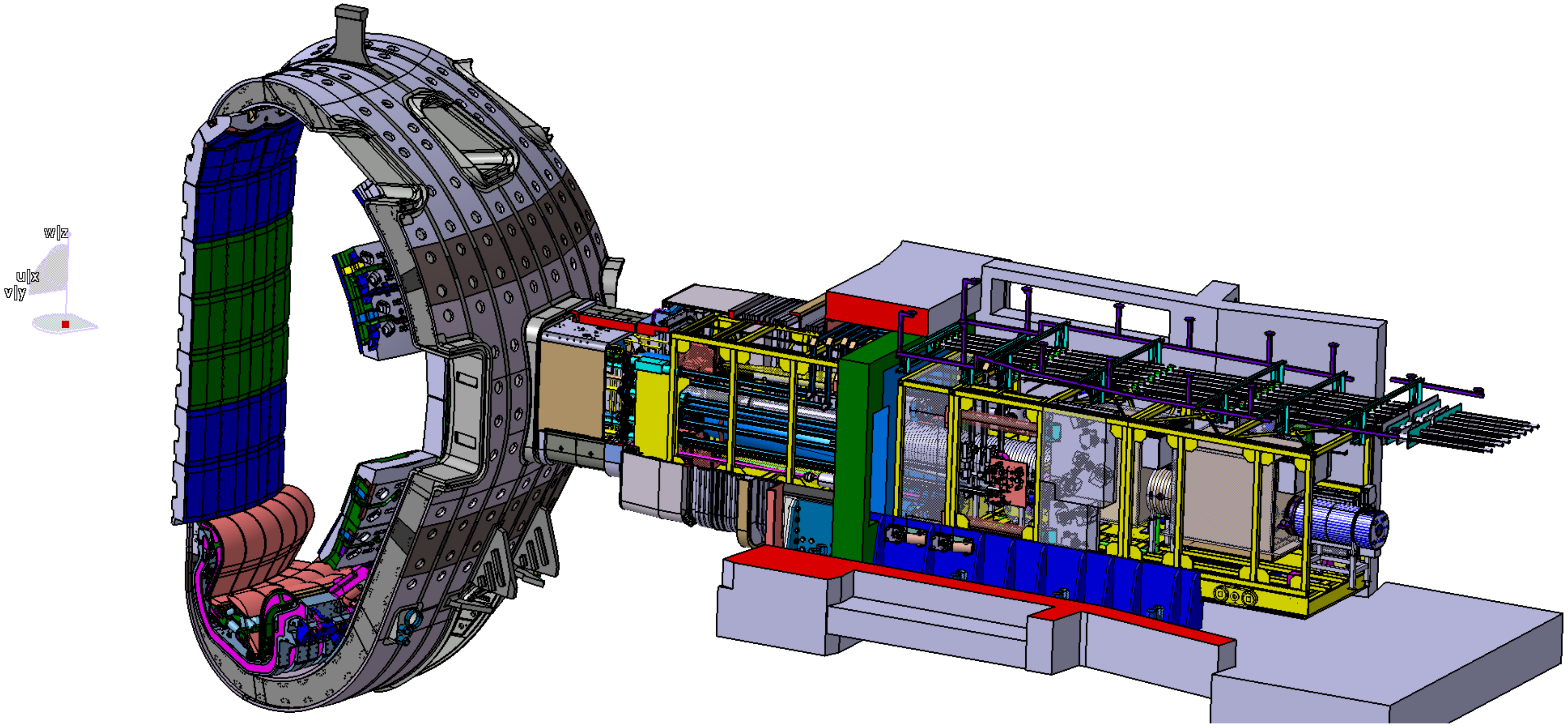


Equatorial port plug
(“plugs” the vacuum vessel)

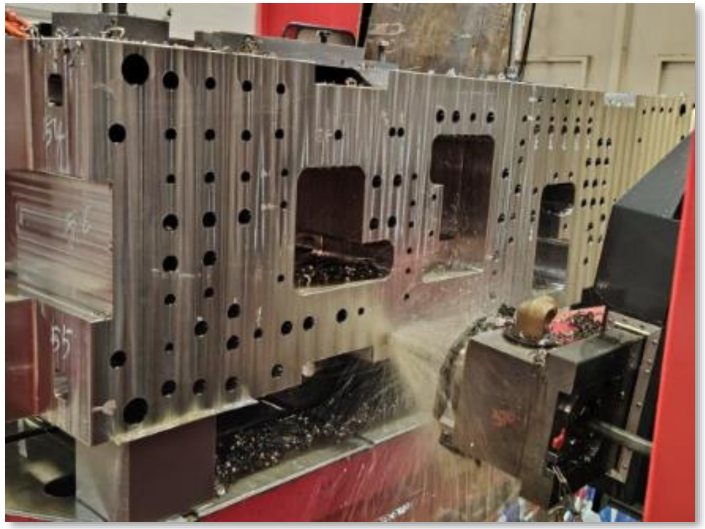
(between vacuum and 1st bioshield)

(between 1st and 2nd bioshield)

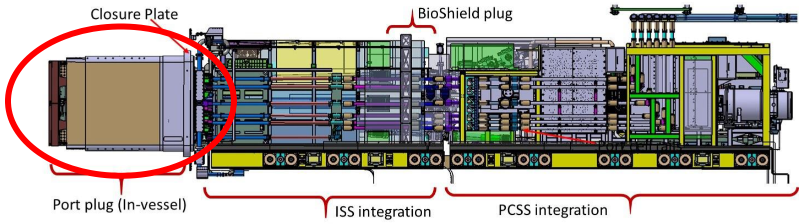
Diagnostic port (contd.)

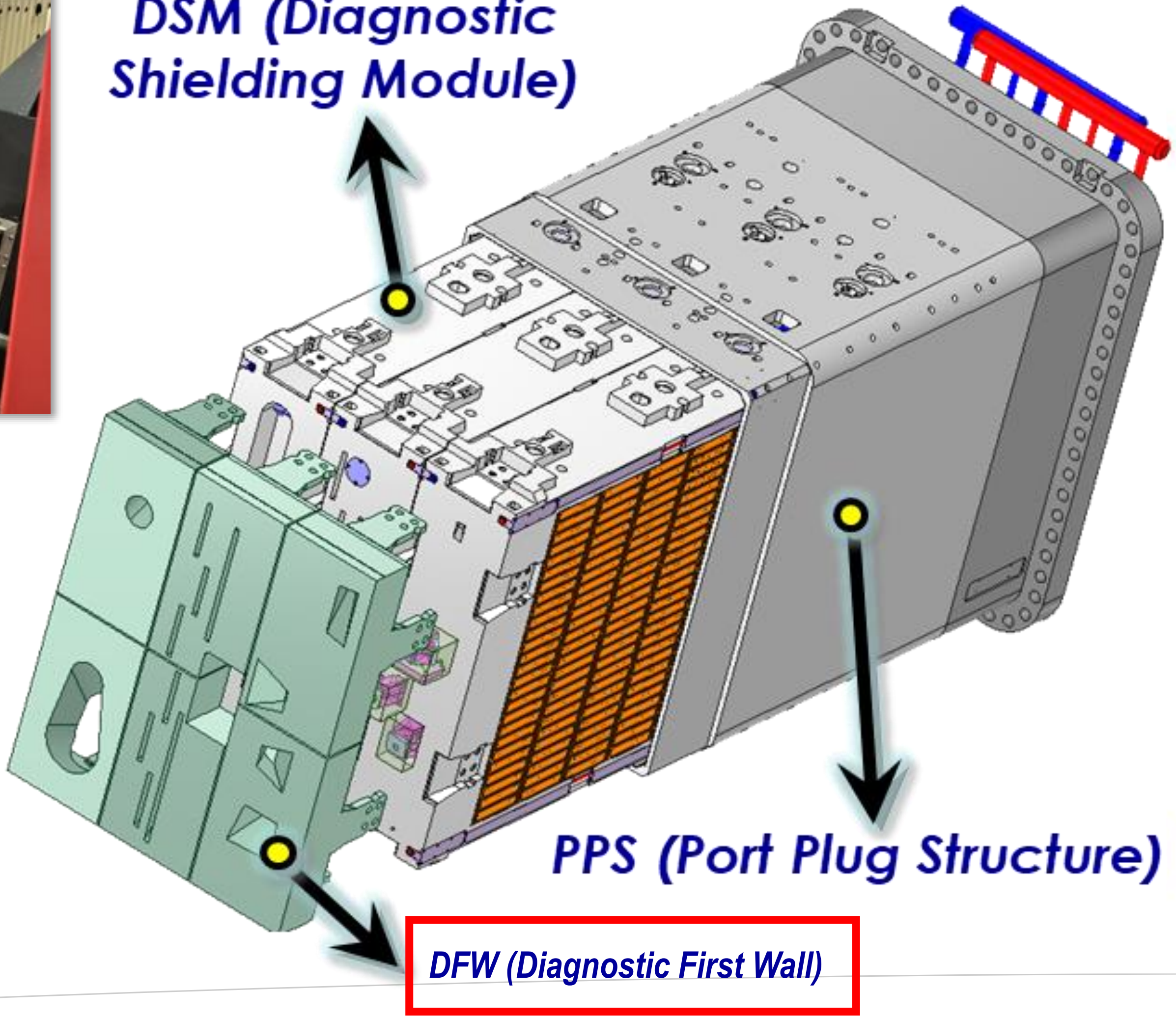


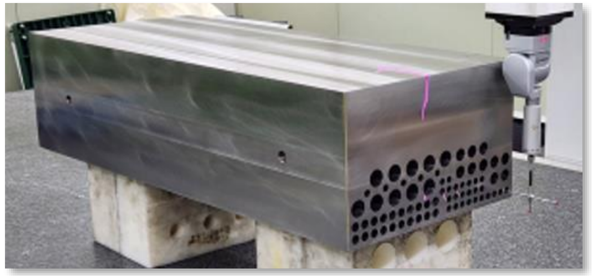
Modular port plug



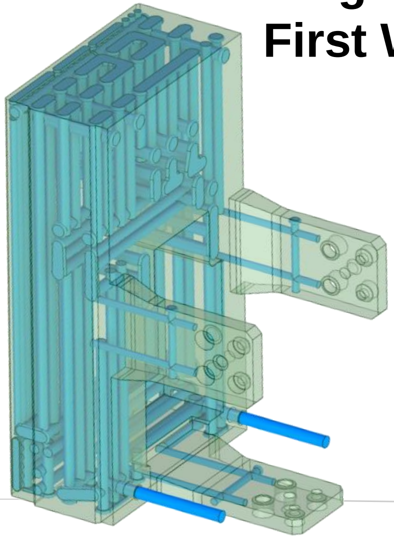
Diagnostic shield module during the gun drilling





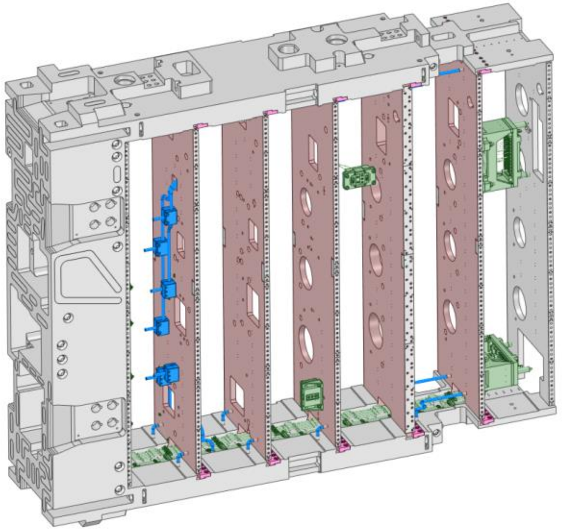


Diagnostic First Wall

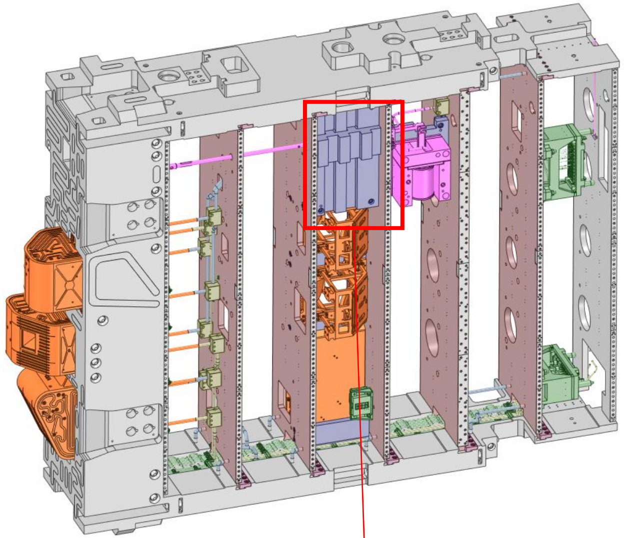


Integrated modular port plug – standardized and versatile

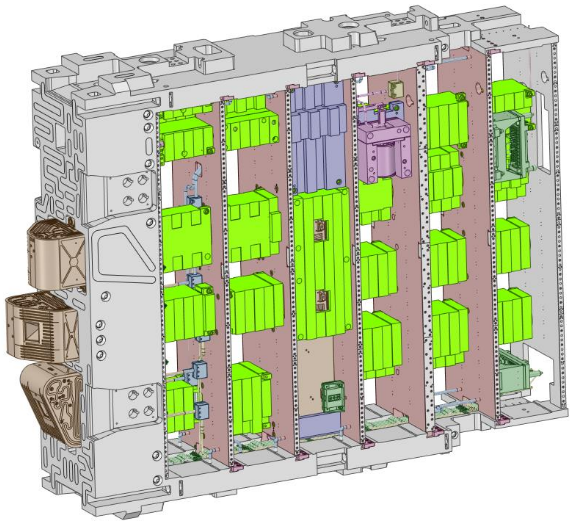
Electrical services



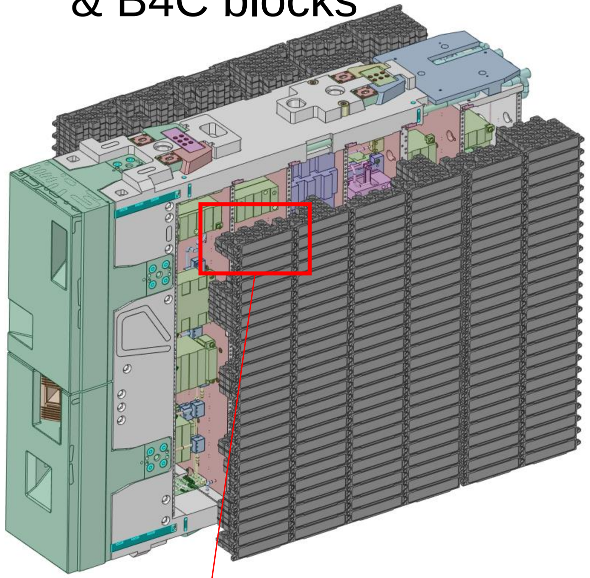
Diagnostic components

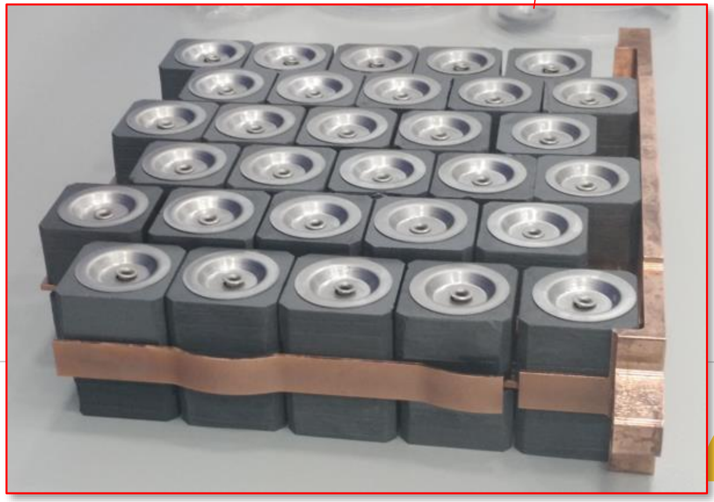


Backfilling



Diagnostic First Wall & B4C blocks





Diagnostics integration – main challenges

ITER is first and foremost a Nuclear Facility (“Installation Nucléaire de Base”) …

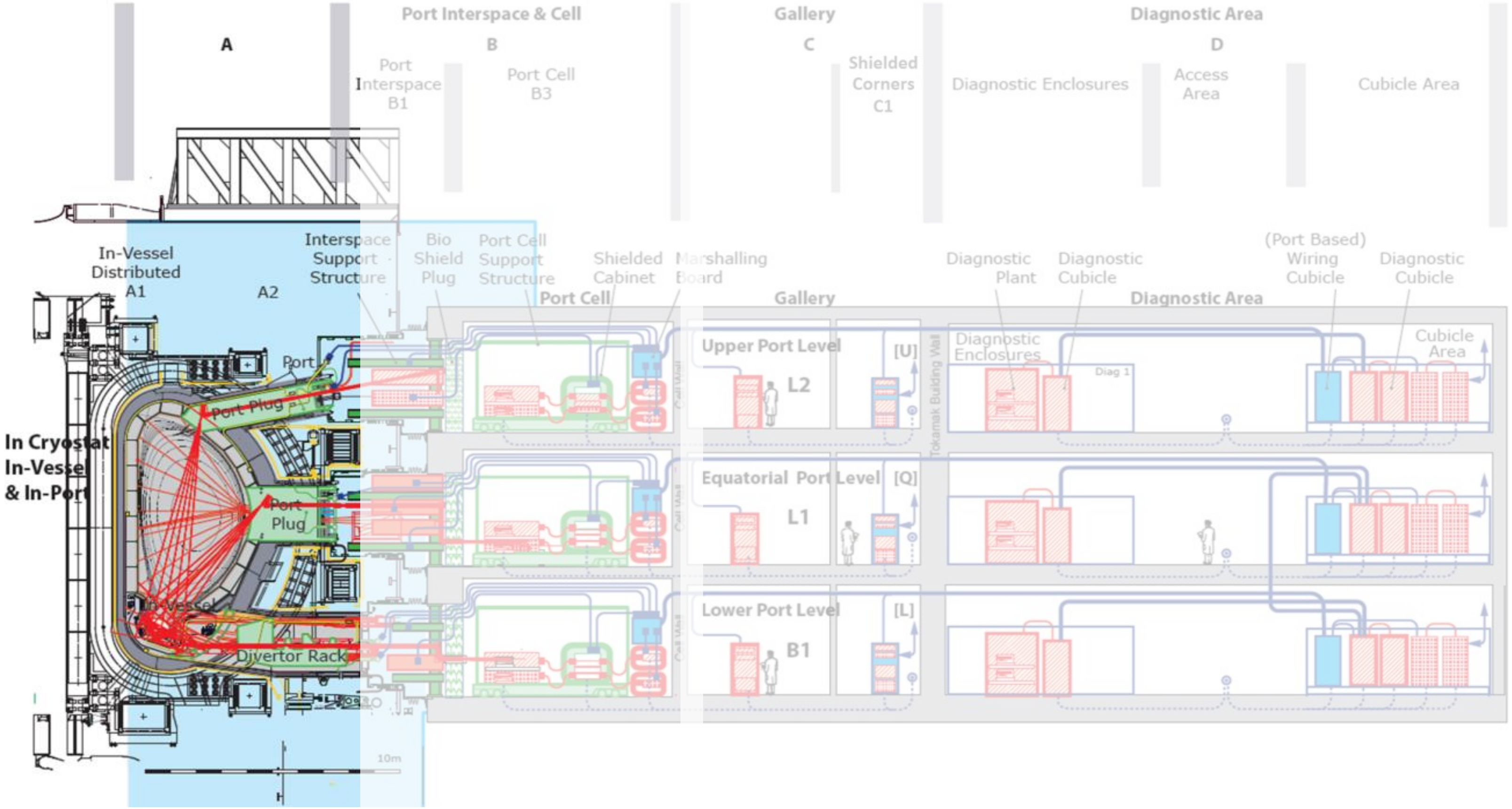
… and only then an experimental science project

- **Nuclear environment** means we need to mitigate transmutation, radiation damage and thermo-electric effects
- Design target: **zero maintenance** (in practice very difficult)
- **Quality requirements are high**, in particular for assembly to the vacuum vessel and vacuum vessel feedthroughs and windows (Protection Important Components)
- **Many interfaces** (machine-diagnostics, diagnostics-diagnostics)
- **Engineering** (remote handling capability, neutron shielding)

…illustrated one by one in the following slides

Zones for diagnostics radiation-hardness

Radiation worst near the vacuum vessel and dropping off with distance and shielding



>10^{12} n/cm^2/s >10^6 n/cm^2/s >10^3 n/cm^2/s <10 n/cm^2/s

A: Transmutation, swelling, embrittlement some metals, high neutron and gamma heat loads → Only radiation hard sensors and cables

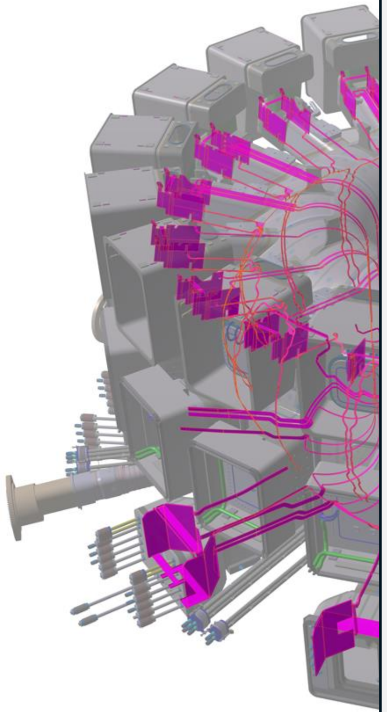
B: Radiation induced attenuation (RIA) of glass, embrittlement of polymers (cables) → Damage to all but the simplest electric/electronic components, unless shielded

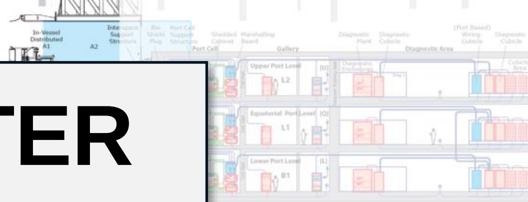
C: Some RIA in glass (fibres) → damage to unshielded COTS electronics

D: No radiation impact anymore → OK for COTS electronics and instruments (spectrometers, lasers, cameras, etc.)

Zone A: Inside the Vacuum vessel and Port Plugs

- Very hig
- No poly

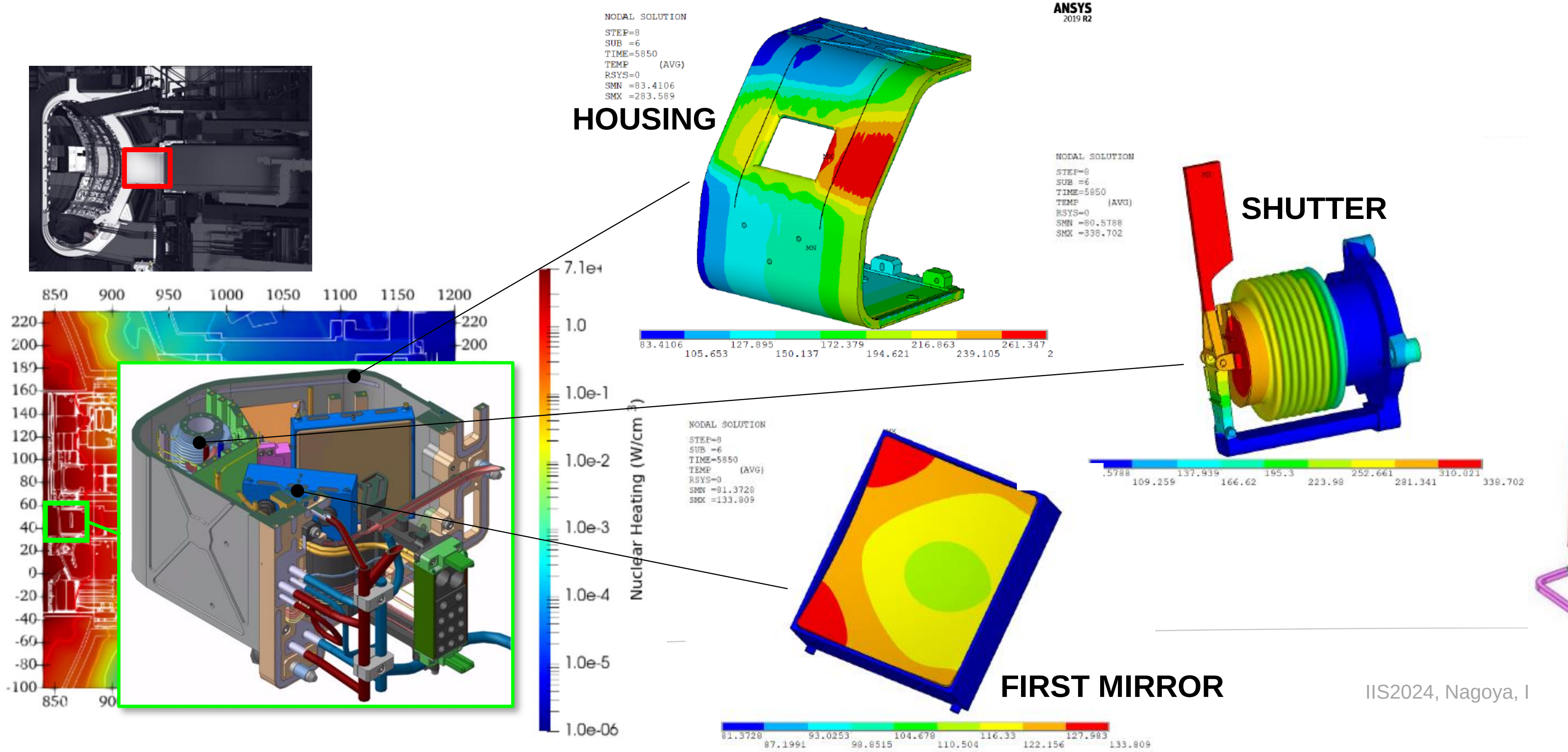


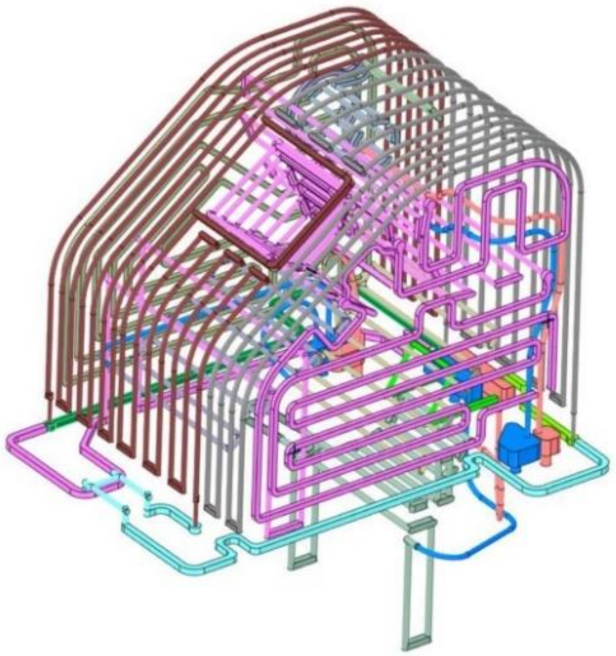


Clamps for electrical looms arrived to ITER last month – more than 100.000 individual components to inspect upon reception!

Zone A: Inside the Vacuum vessel and Port Plugs

- Very high radiation severely limits material choices
- No polymers (not even Kapton, except on the very boundary). All metal and ceramics.
- Design must cope with thermal stresses and deformations …
  - → Structural Integrity
  - → Impact on measurement performances (e.g. deformations of mirrors, stray light)





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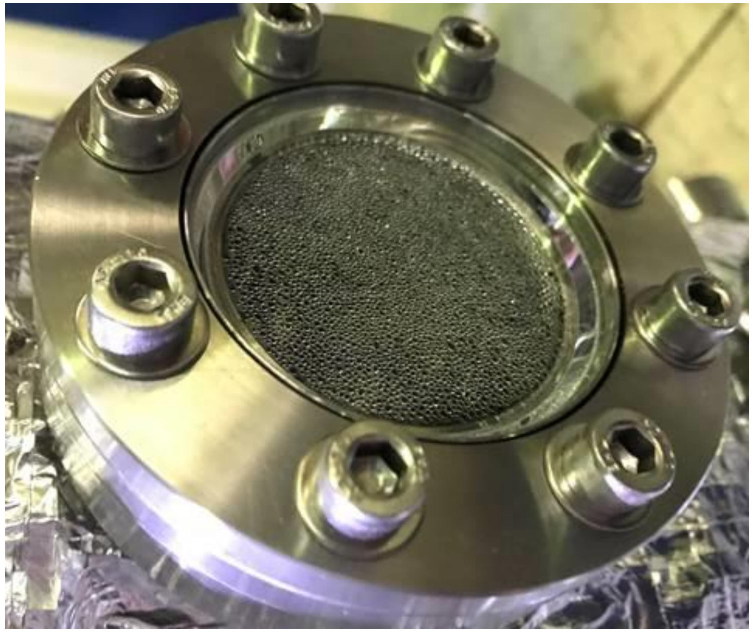
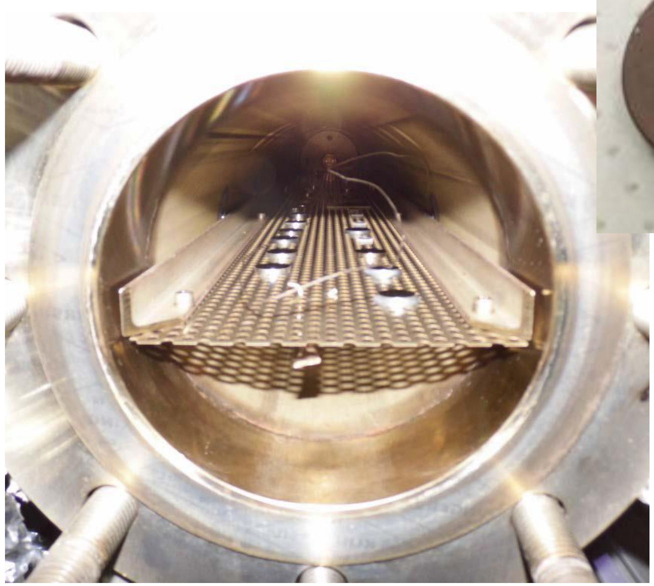
  - → Impact on measurement performances (e.g. deformations of mirrors, stray light)
- Exposure to in-vessel water leaks → hot steam and humid conditions



Steam exposure tests on vacuum window



CuCrZr substrate + Rh coating after steam and humidity exposure

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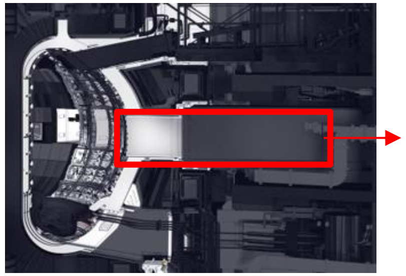
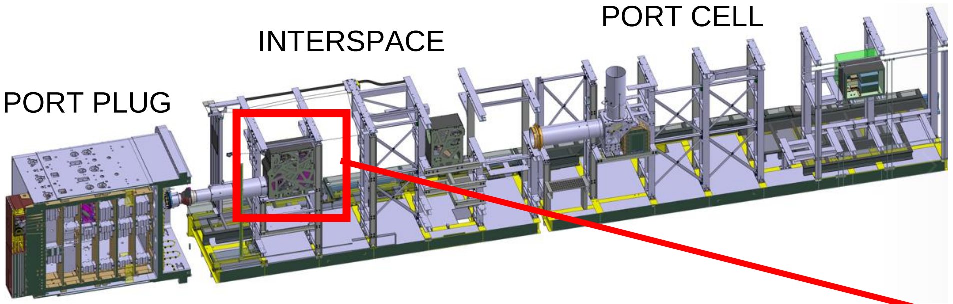
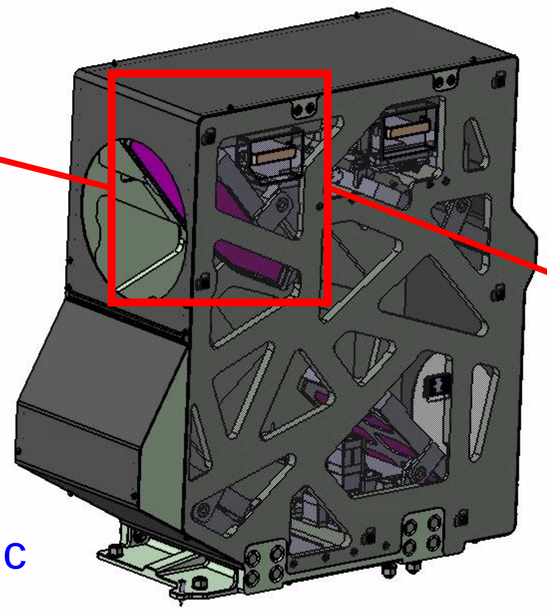
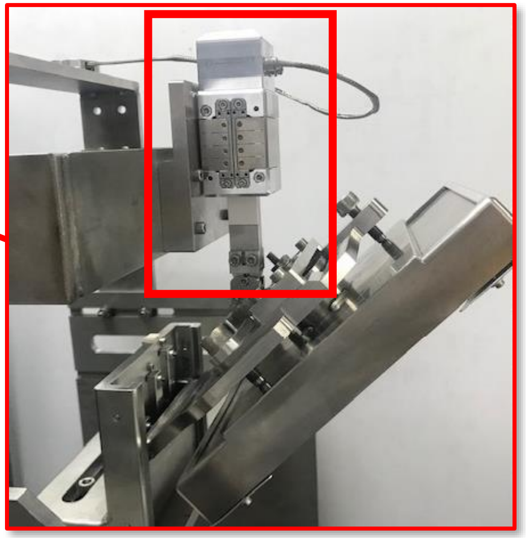
Zone B: Interspace and port cell - radhard sensors

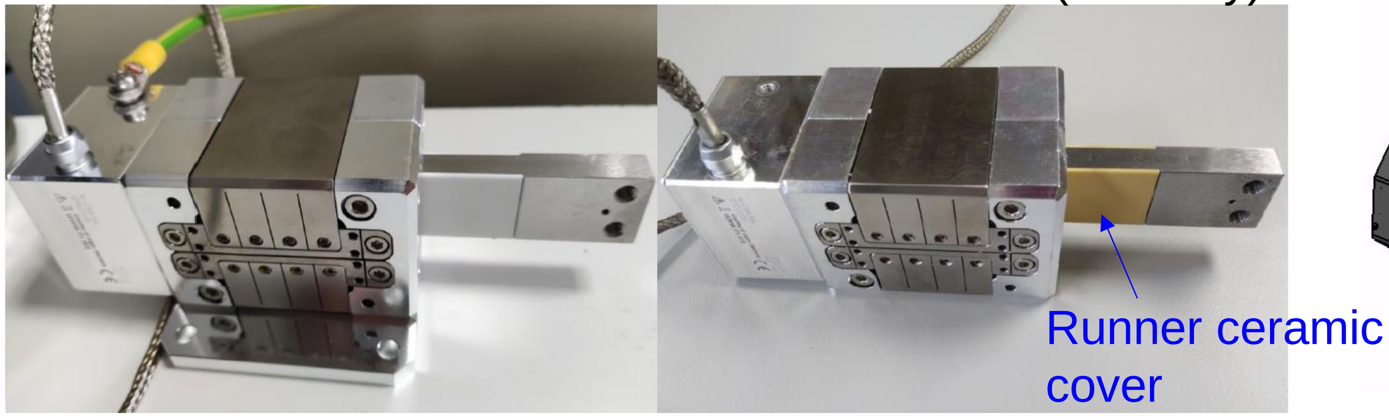
- Still rather high temperatures (up to 50 ˚C)
- Radiation too high for most polymers except Kapton, PEEK, etc – special cables and o-rings needed





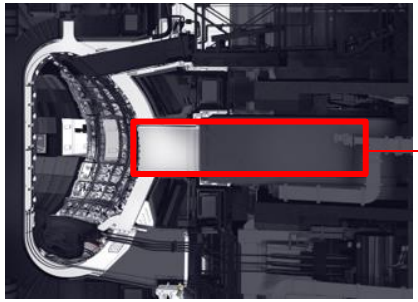


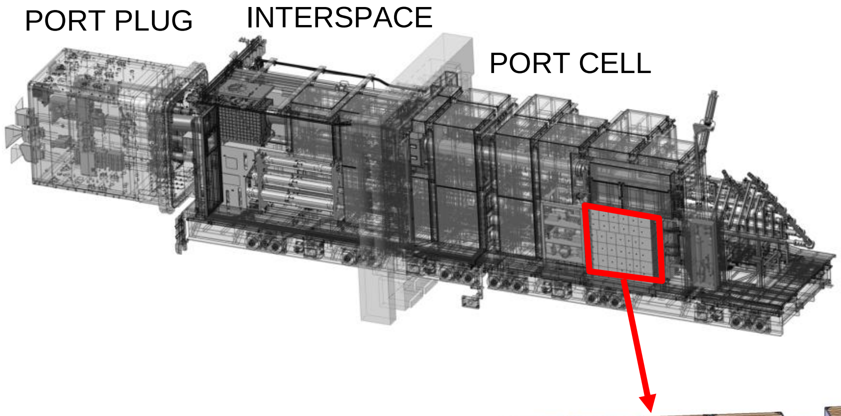


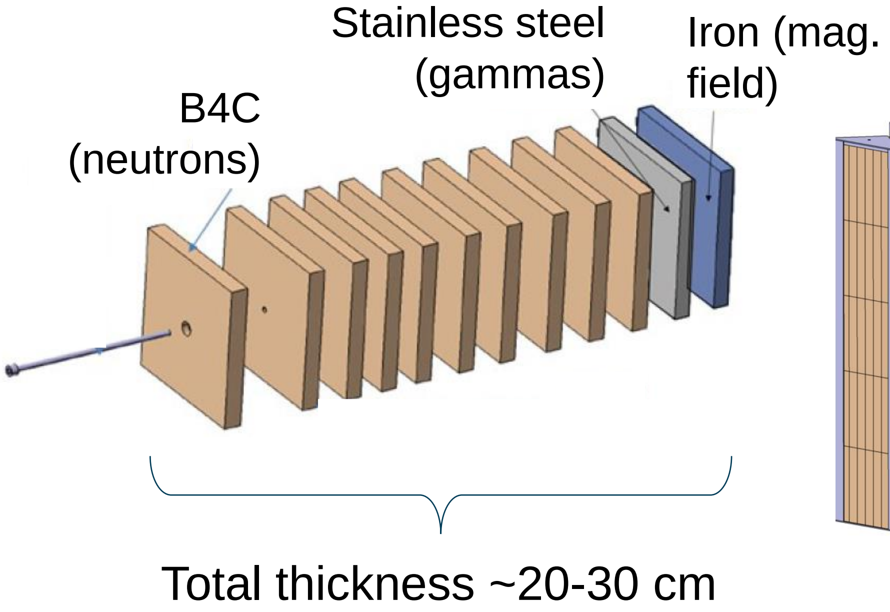


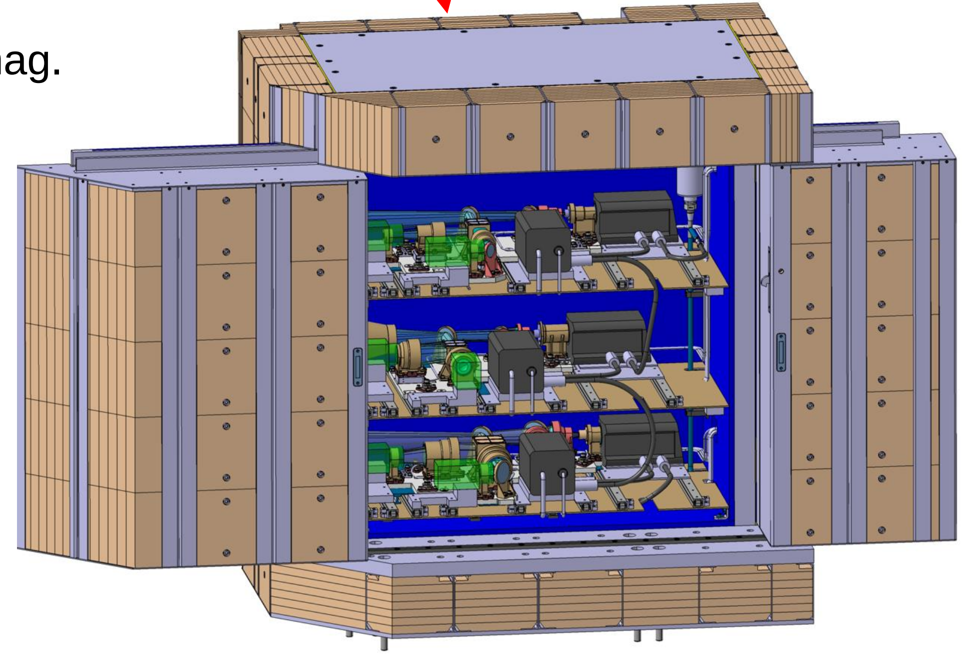
- About 10% drop in the maximum velocity after irradiation → insignificant impact on the functionality

Zone B: Interspace and port cell – local shielding

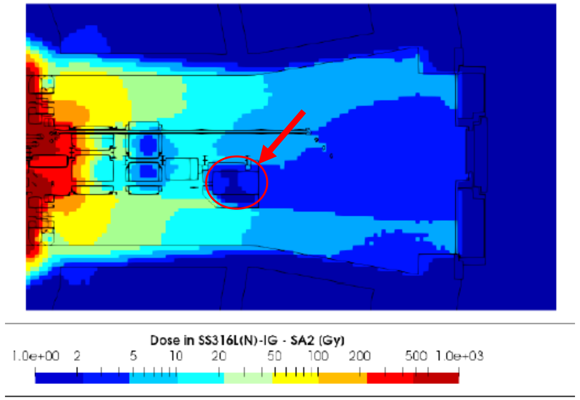




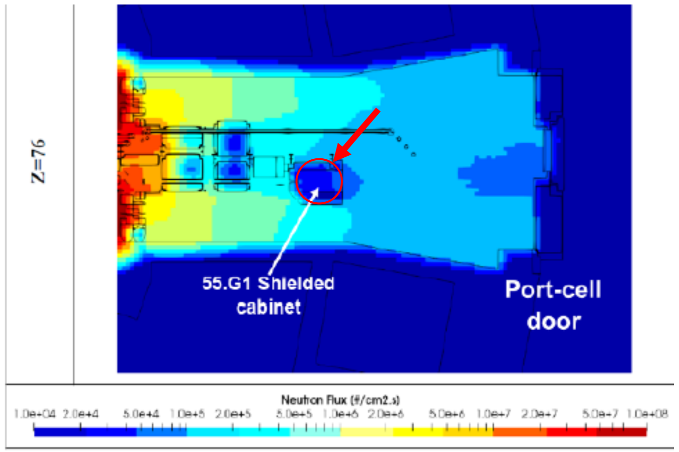




Gamma dose

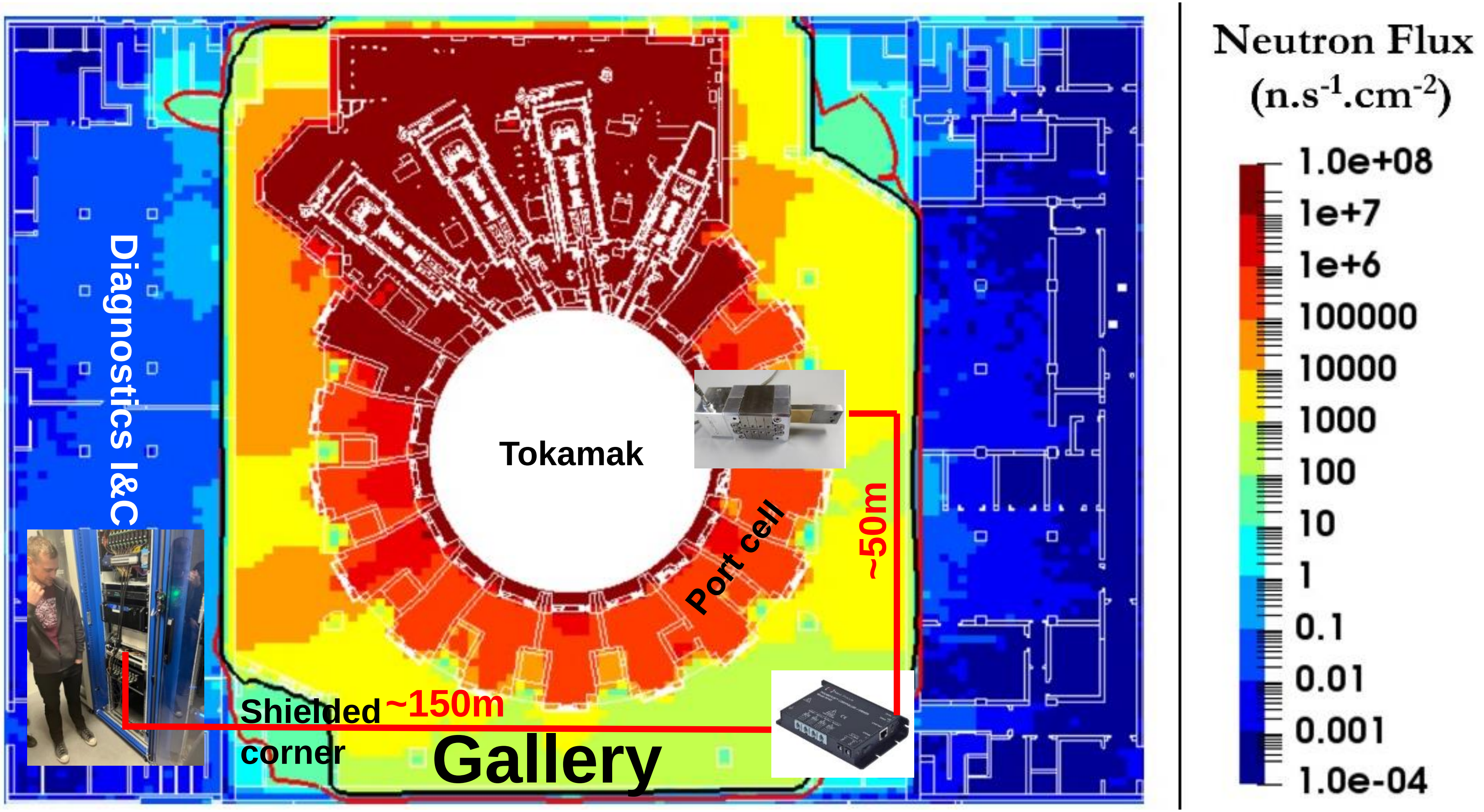


Neutron flux



Zone C: Gallery

- Still significant radiation especially during cask transfer
- Shielded corners ok for most electronics, but remote and space limited

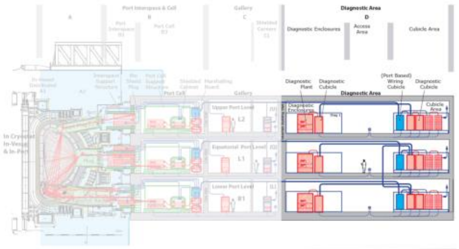


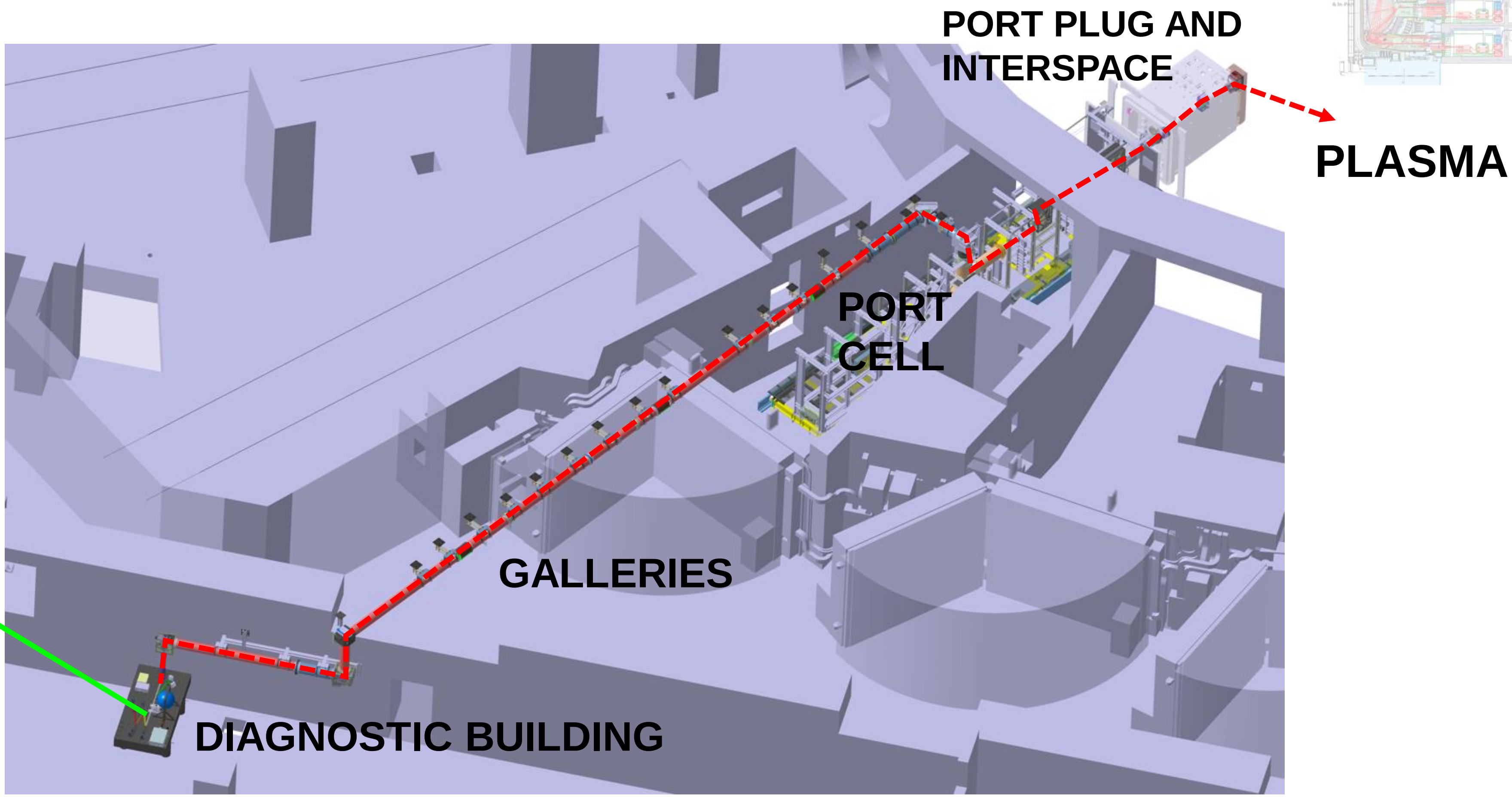
Only simple Radhard components in port cell

Simple controllers/pre-amps in shielded corner

Complex I&C in Diagnostic Building

Zone D: Diagnostic Building



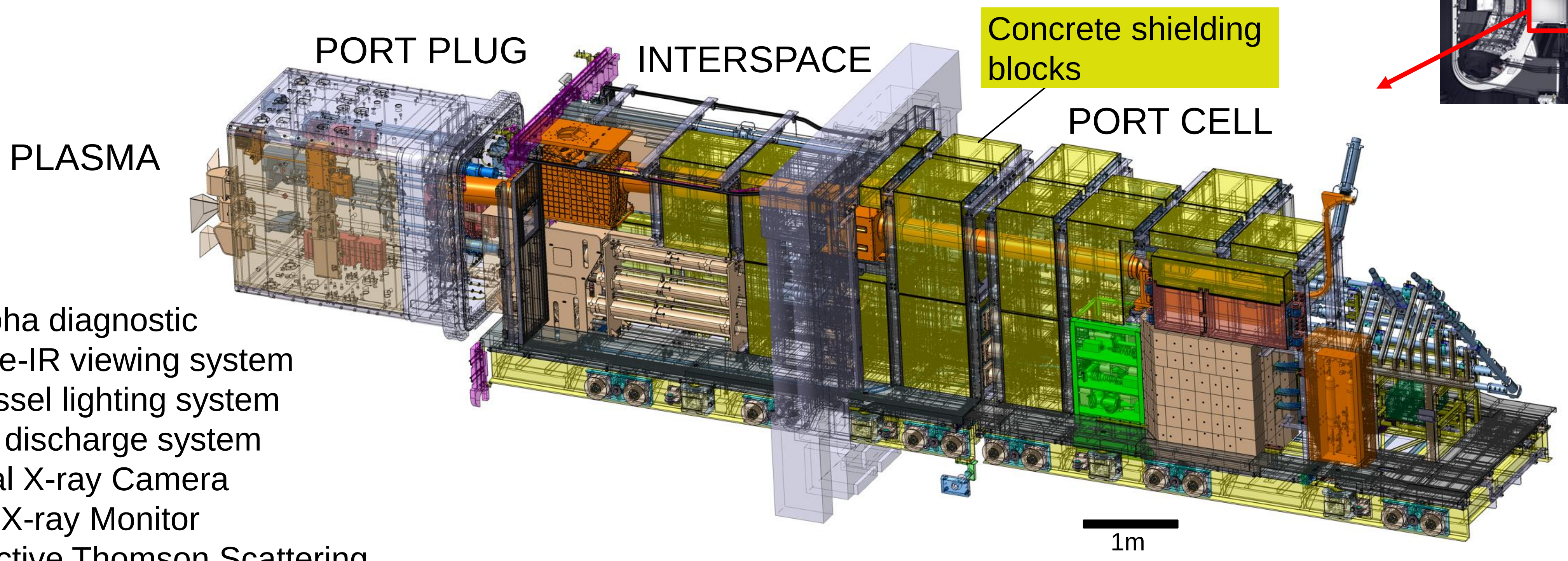


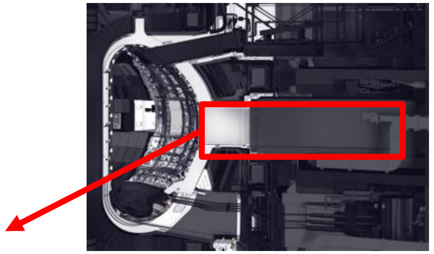
- 40 meters, 17 mirrors and 18 lenses from plasma to optical table!

Integration challenges

Machine-diagnostic integration challenges – in diagnostic ports

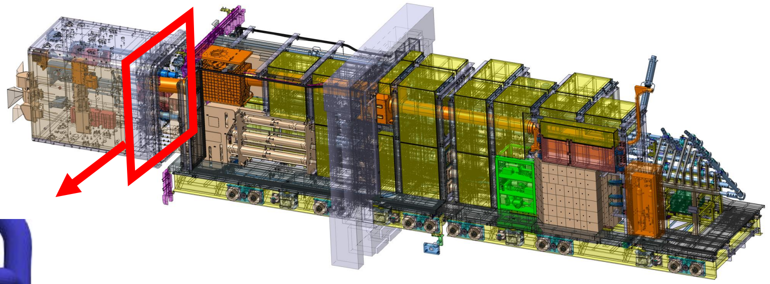
- Up to 8 diagnostic per single port + support structures, services and instrumentation
- Space needs to be used very efficiently
- All unused space filled with shielding blocks



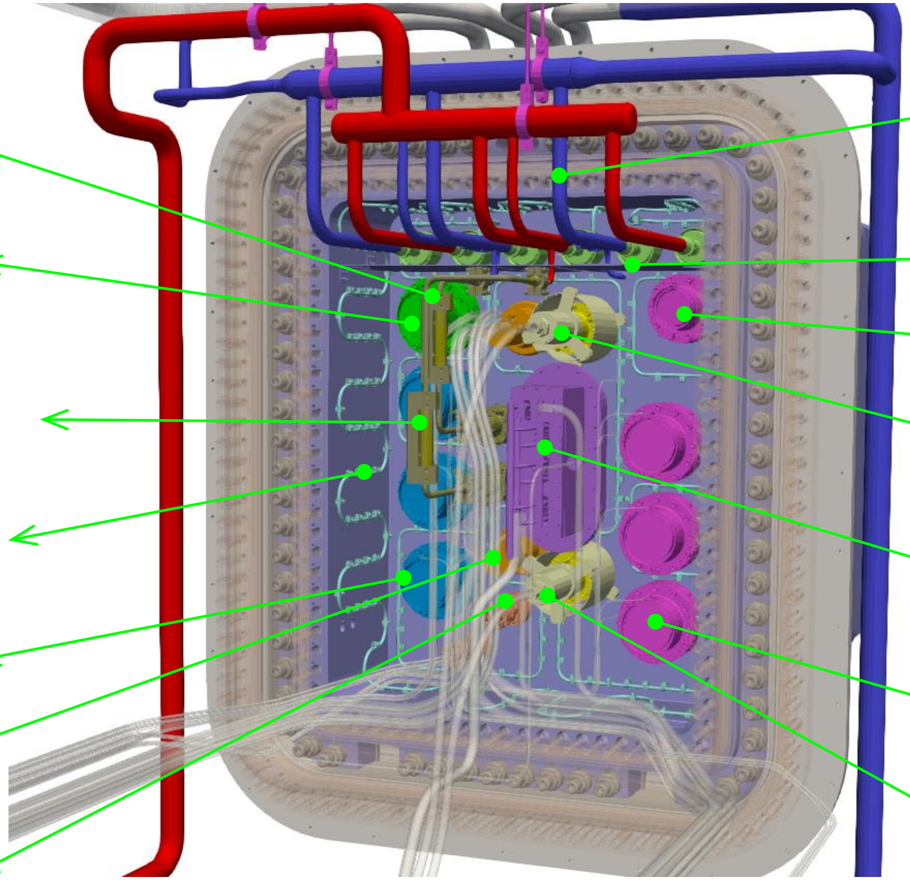


- H-Alpha diagnostic
- Visible-IR viewing system
- In-vessel lighting system
- Glow discharge system
- Radial X-ray Camera
- Hard X-ray Monitor
- Collective Thomson Scattering

Machine-diagnostic integration challenges – in diagnostic ports (contd.)



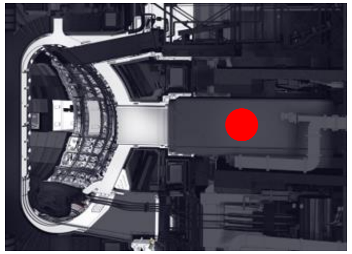
Example of integrated closure plate (height ~2m)

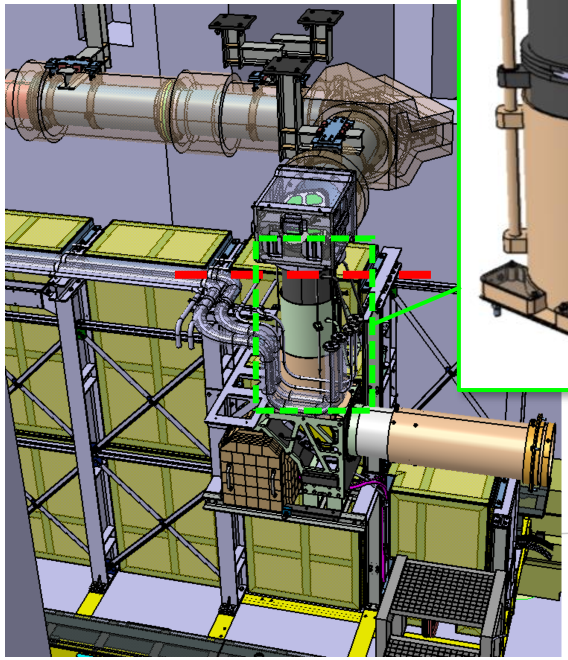


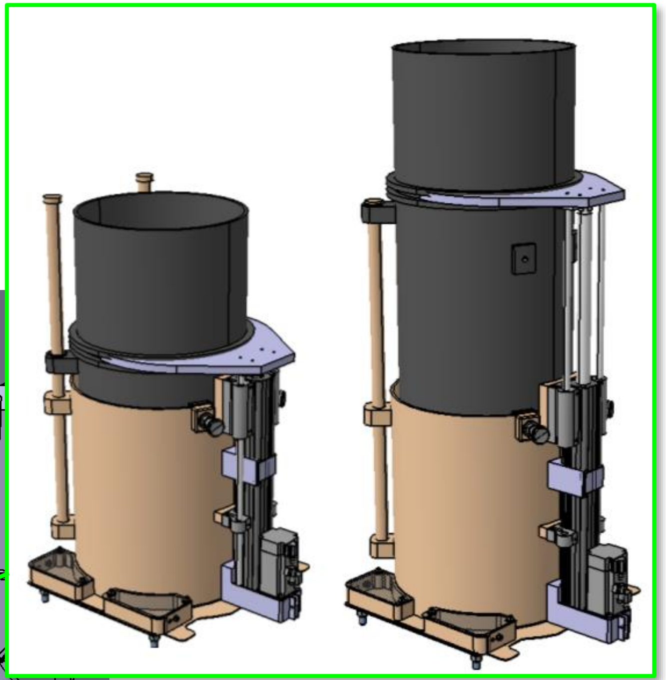
Machine-diagnostic integration challenges – in diagnostic ports (contd.)

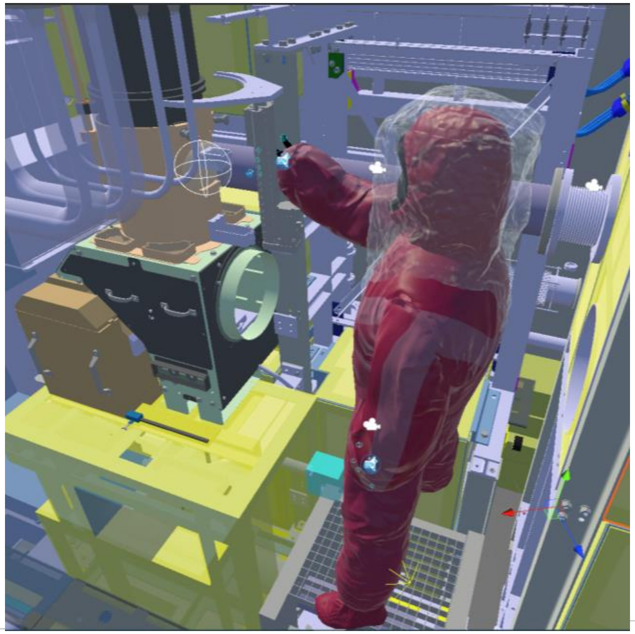
Exposure to maintenance workers shall be limited and ideally avoided
If really no other way:

- Use of protective suits
- Design to minimize maintenance needs – demonstrated by enhanced VR and/or mock-ups









Camera view

Eye view

Machine-diagnostic integration challenges – in diagnostic ports (contd.)

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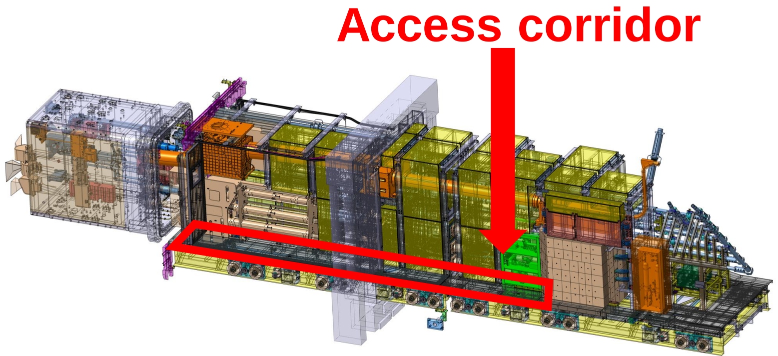
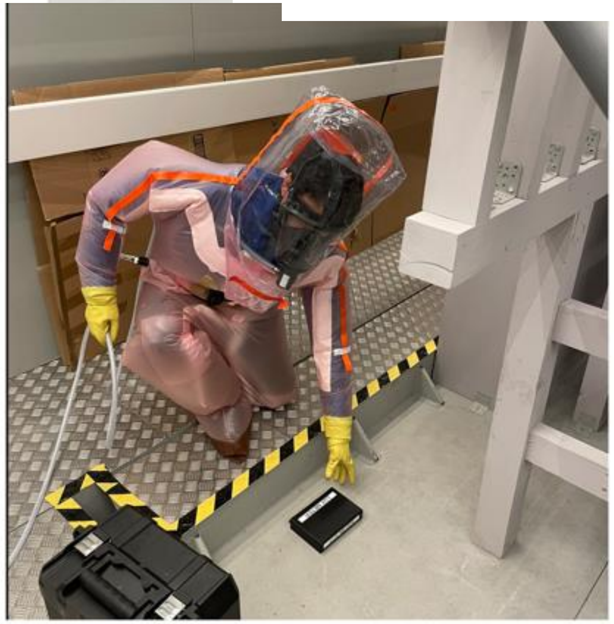
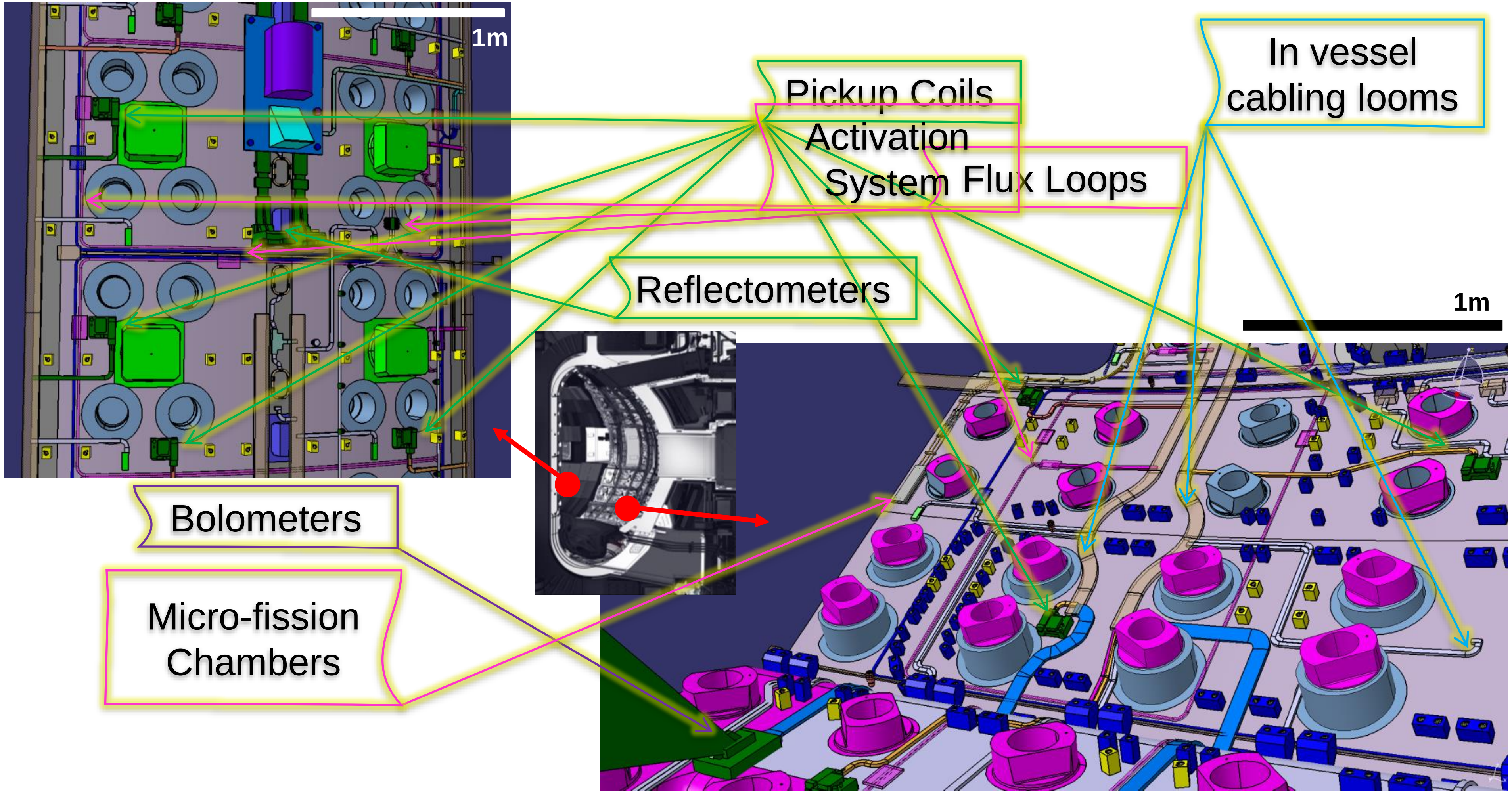
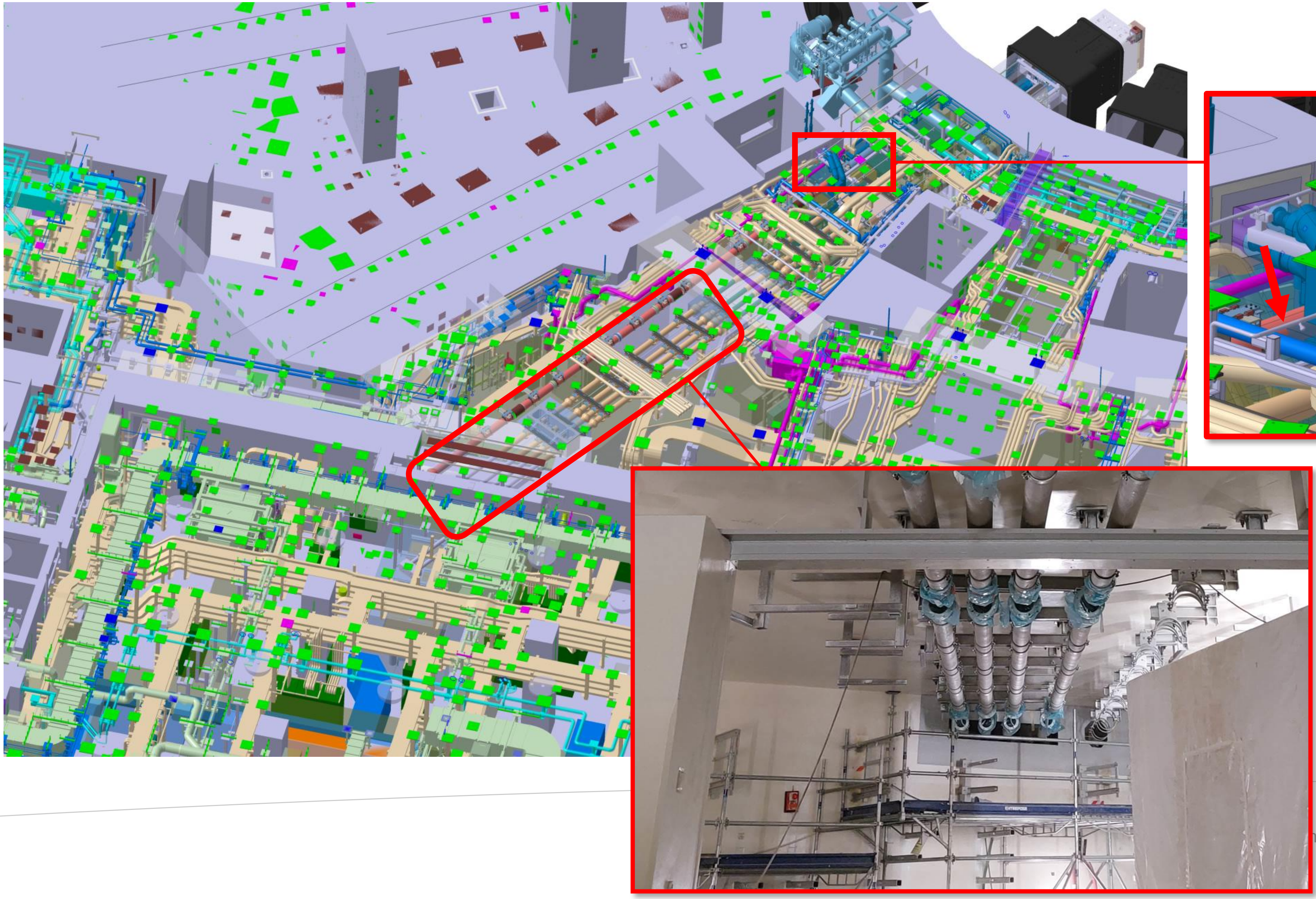


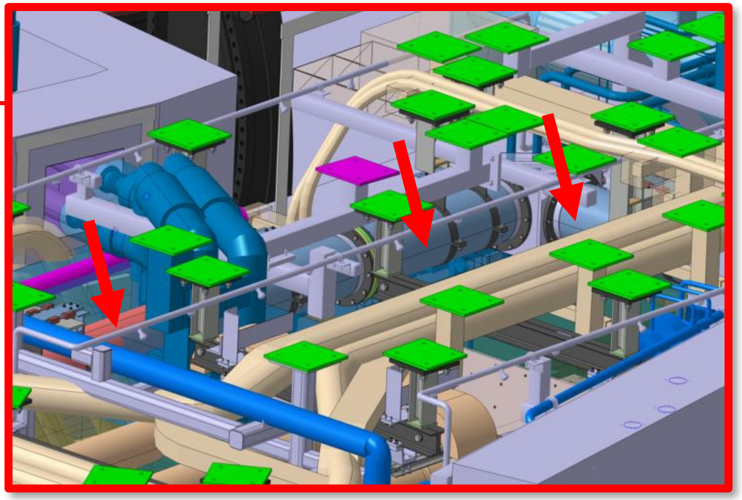


Machine-diagnostic integration challenges – on the vacuum vessel



Machine-diagnostic integration challenges – in tokamak galleries

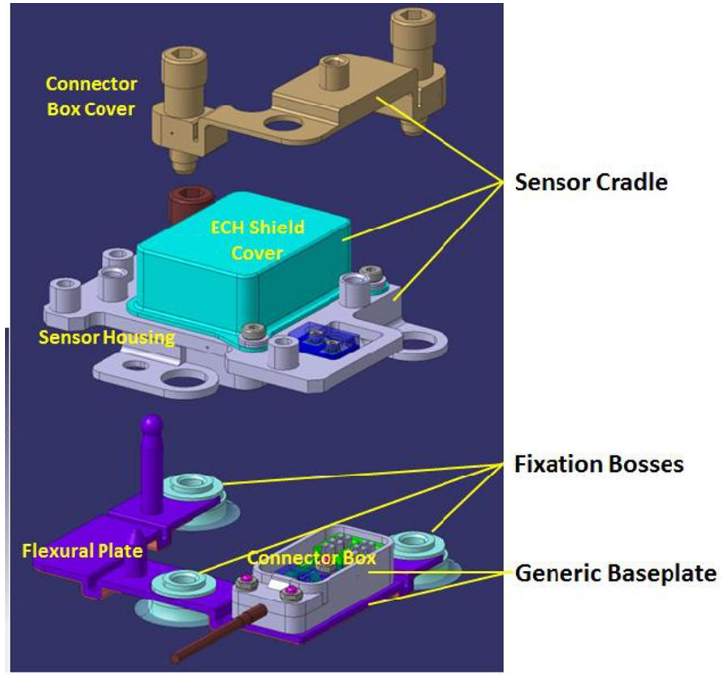


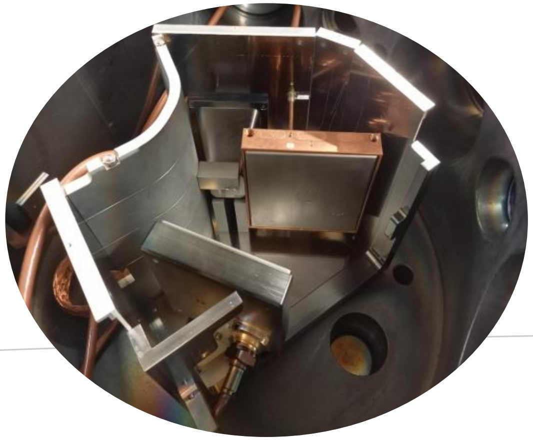


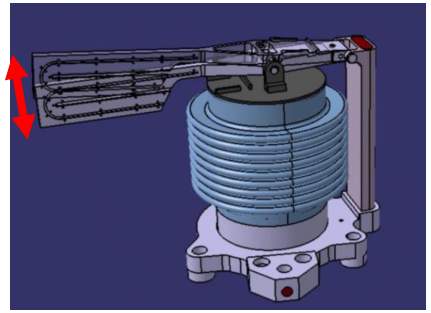
How to tackle “zero” maintenance?

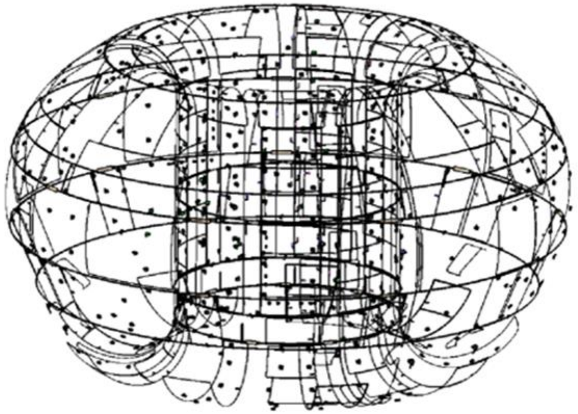
Where maintenance is not possible (port plugs, cryostat, behind first wall blankets):

- Critical items: designed for **Remote Handling replacement**
- **In-situ protection and recovery** - shutters, mirror cleaning system
- **Redundancy** where replacement is not possible (e.g. magnetic sensors in cryostat)









Diagnostics progress

Diagnostics Progress – Big picture

Review	Since 2010	2022
Conceptual design	73	2
Preliminary design	81	11
Final design	81	7
Manufacturing readiness	35	17
Total	**270**	**37**

- Largest number of reviews amongst ITER systems by far
- Most diagnostics are in the preliminary and final design phase
- >20 diagnostics are already in the manufacturing phase - some installed

Examples of diagnostic components already manufactured

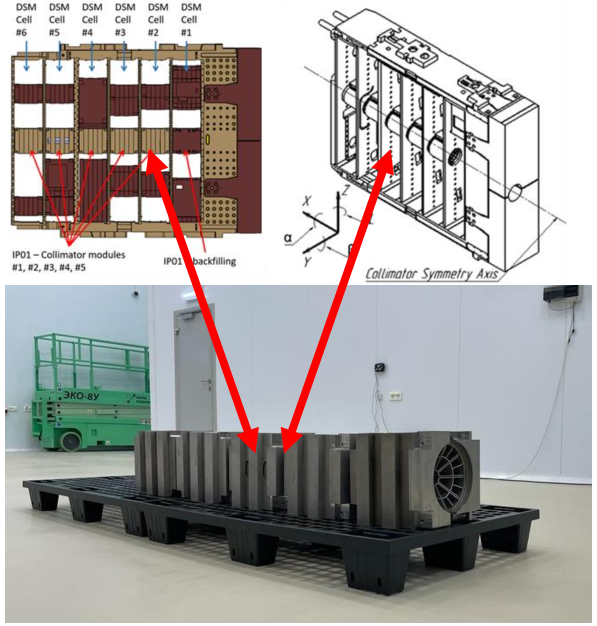
The big and heavy…

Port plugs

Multi-ton weight, multi-m^3 volume, but accurately machined to sub-millimeter tolerances.

Port Plug Test Facility (PPTF) vacuum tank

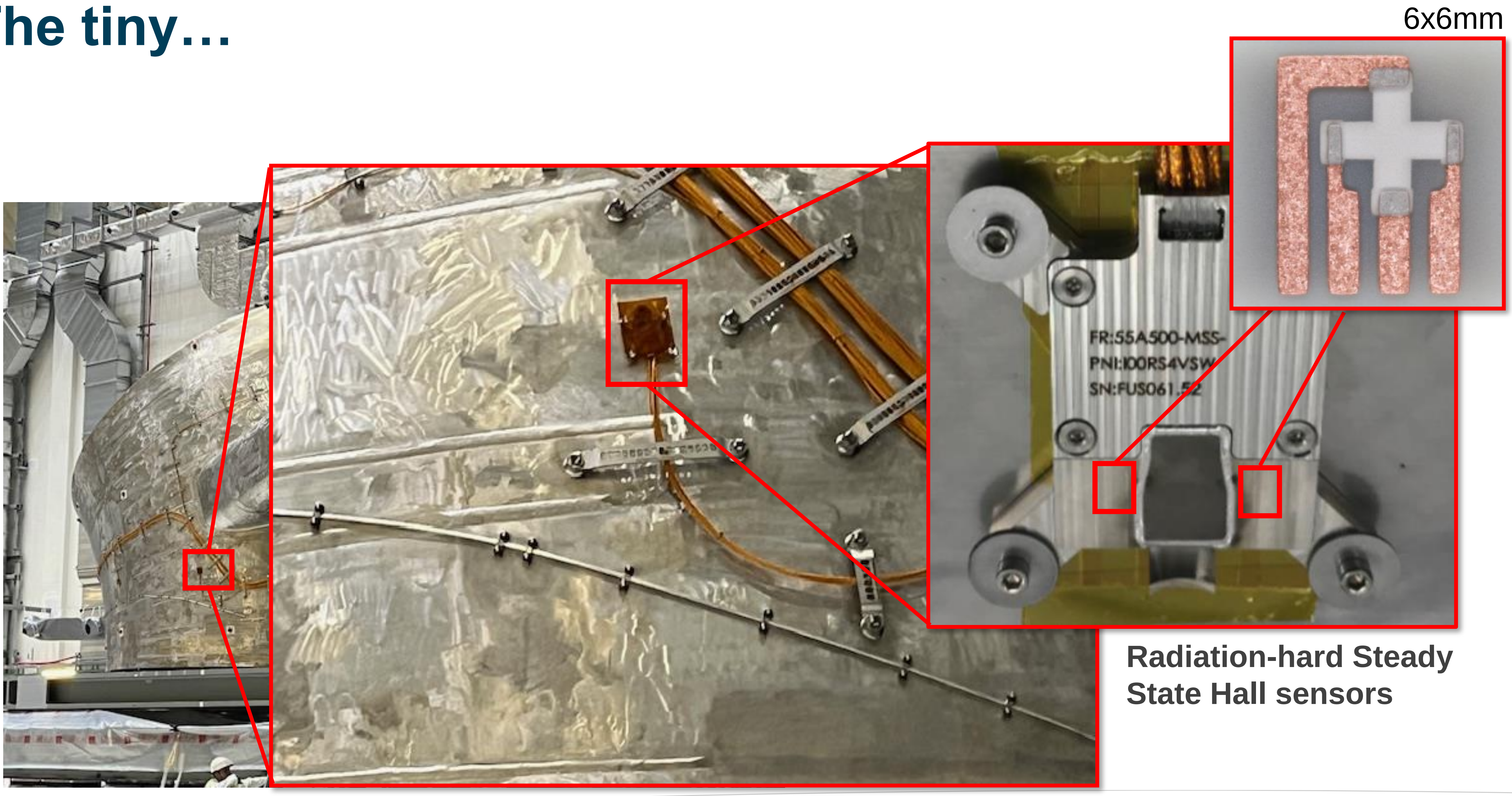
Built to reproduce the same vacuum and temperature conditions like in the Vacuum Vessel of the tokamak (10^{-5} Pa and thermal cycling between 20°C and 240°C at +5/-7°C/h).



Neutral Particle Analyzer

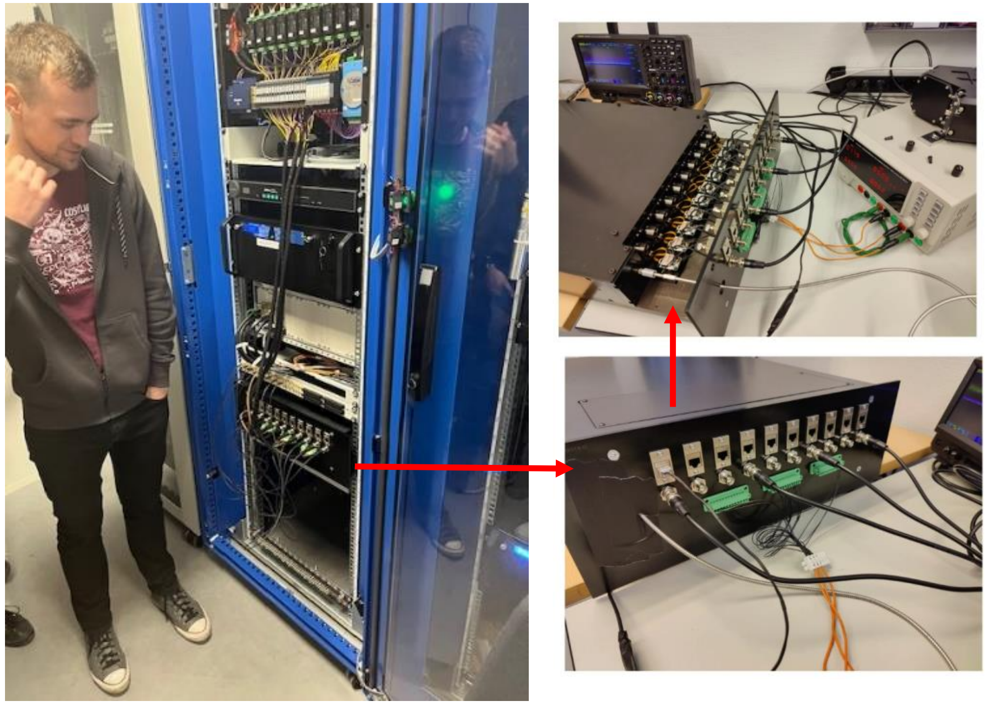
Segmented with Tungsten blades to limit neutron streaming and split in multiple pieces to enable DSM integration.

The tiny…



Radiation-hard Steady State Hall sensors

The (opto-)electronic



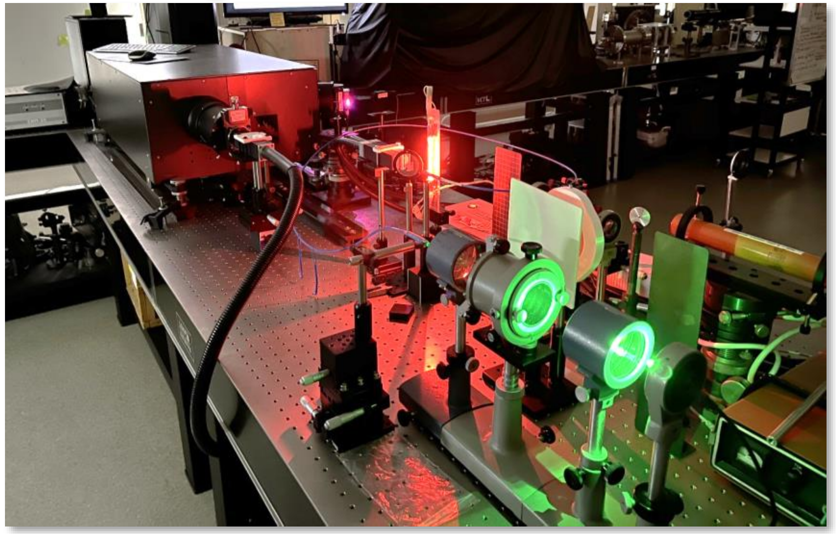
Polychromator and control cubicle

10-channel filter-based spectrometer for Bremsstrahlung and strong line radiation

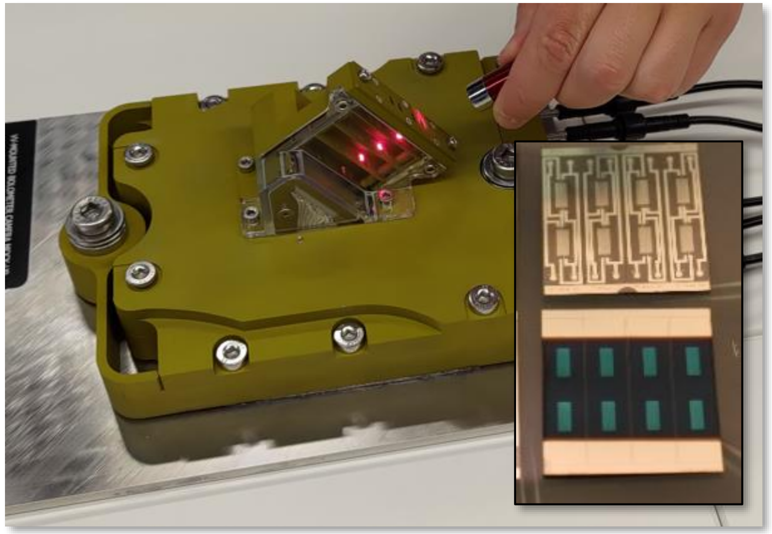
Magnetic diagnostic cubicle at Factory Acceptance Testing

…and large number of mock-ups and prototypes

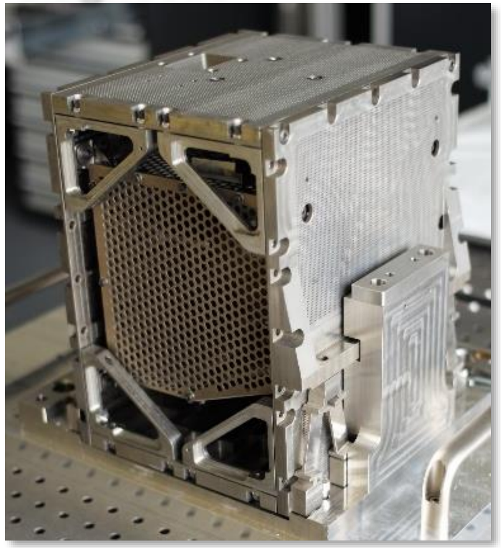
Edge CXRS: Full scale intensity and wavelength calibration scheme mock-up



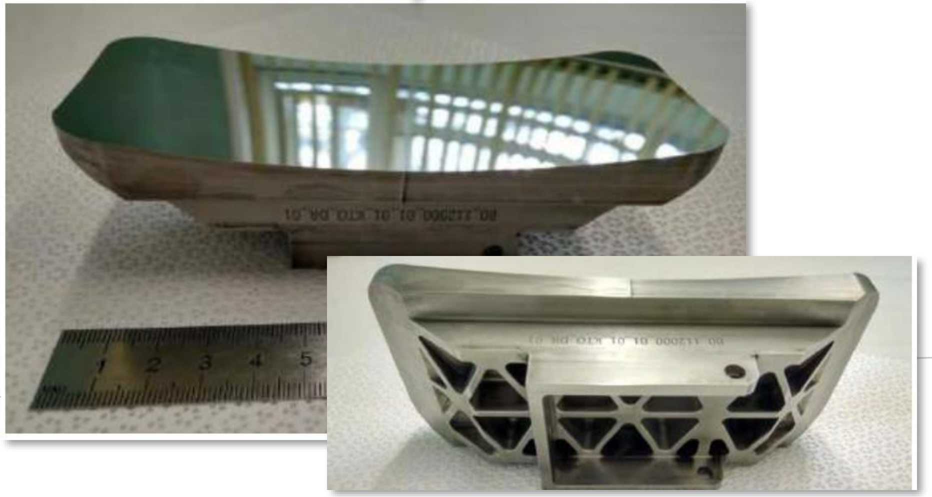
Vacuum-vessel bolometer camera with sensors



Mirror box of the Hα diagnostic

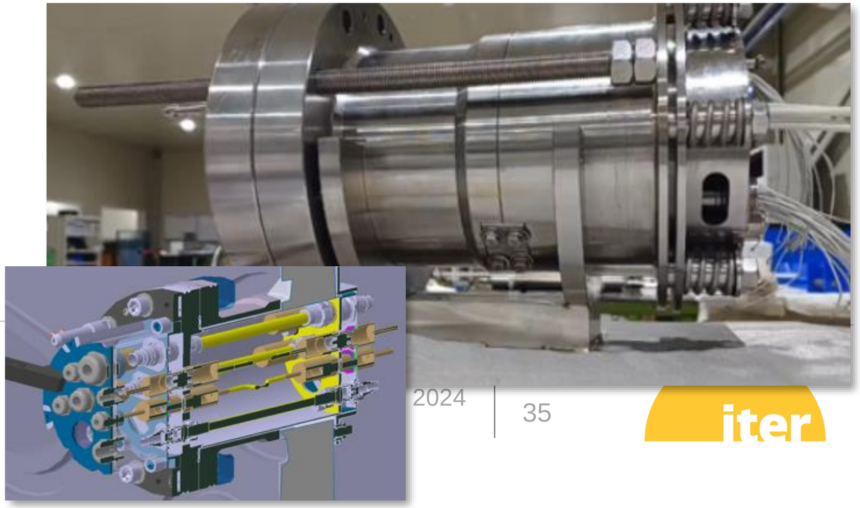


Hollowed out Molybdenum mirror



Actively cooled Molybdenum mirror

Electrical feedthrough prototype



Conclusions

- Integration of diagnostics on ITER brings **new challenges** unprecedented in most of the current tokamaks
  - Nuclear environment
  - Limited or zero maintenance
- **Resolved with dedicated R&D and standardization**
- Number of ITER diagnostics are past Final Design Reviews. Some diagnostics are already manufactured and installed.
- **Moving forward thanks to teams within and outside ITER!**